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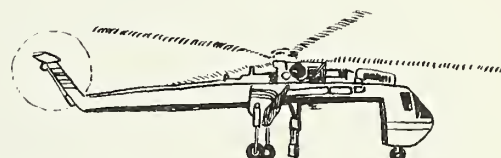
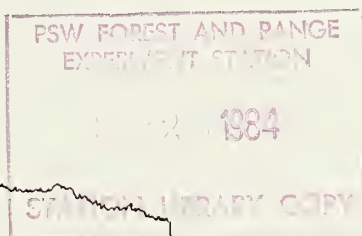
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# Estimating Tree Bole and Log Weights From Green Densities Measured With the Bergstrom Xylodensimeter

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## Abstract

**Waddell, Dale R.; Lambert, Michael B; Pong, W. Y.** Estimating tree bole and log weights from green densities measured with the Bergstrom xylo densimeter. Res. Pap. PNW-322. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984**. 18 p.

The performance of the Bergstrom xylo densimeter, designed to measure the green density of wood, was investigated and compared with a technique that derived green densities from wood disk samples. In addition, log and bole weights of old-growth Douglas-fir and western hemlock were calculated by various formulas and compared with lifted weights measured with a load cell attached to a front-end loader. The Bergstrom xylo densimeter accurately measured green wood density and is useful for estimating log weights.

**Keywords:** Log measurements, boles, wood density, cubic volume measure, measuring equipment, old-growth stands.

## Summary

Aerial logging of heavy material requires accurate estimates of load weight for safety and for economical production. Green wood density is an important element in estimating log and tree bole weight. This study was conducted to evaluate the Bergstrom xylo densimeter, an instrument consisting of a calibrated hydrometer and flotation chamber that measures the green density of an increment core. Results obtained with the xylo densimeter were compared with results using the standard wood disk technique. Log weights calculated from measured green densities multiplied by the volume of the log were compared with actual weights. Calculated weights of tree boles were also compared with lifted weights. Bias and accuracy statistics were also presented.

The study was conducted in the Wind River Experimental Forest, Gifford Pinchot National Forest, in southwest Washington; green density and log weights of both Douglas-fir and western hemlock were tested.

Results indicated acceptable values of bias and accuracy for many applications in aerial logging. Further refinements in methodology and additional research are recommended. Examples of how to apply the techniques are provided.

## Introduction

In the last 20 years, there has been an emphasis in forestry on developing aerial logging systems including heavy-lift helicopters, balloons, and airships. They increase yarding efficiency through larger lift capacities, better access to remote timber, and less road construction. The result can be lower primary transportation costs per unit volume of timber with potentially less impact on the environment.

For most timber harvesting systems, a substantial increase in production rates can be accomplished by the accurate estimation of log weights (Conway 1976, Dykstra 1975, Hartsough and others 1983). In cable yarding systems, the size of the cable line is often dictated by the weight of the heaviest logs in a sale unit. Poor estimates of load weights in aerial logging periodically result in aborts caused by overloading and in extra flight hours when payloads do not approach lift capacity; therefore, the larger the lift capacity of the airborne system and the higher the percentage of time spent transporting logs from the woods to the landing, the greater the requirement to accurately estimate the weight of the load.

Although accurate determination of log weights is critical to the success of aerial logging systems, estimation of log weights has received limited research attention. The need for accurate weights was recognized in the early 1960's when weight scaling and heavy-lift aerial logging attracted the interest of foresters.

Generally, the two variables required to provide an estimate of the weights of the whole bole or of segments are volume and green density (dry density plus moisture). This paper deals primarily with the measurement of green density and represents one step in a system that will eventually help solve various problems related to the prediction of weight.

The Bergstrom xylodensimeter<sup>1/</sup> was designed to estimate the green density of wood in the field. Bergstrom developed the device after observing partially submerged logs in a millpond. He noted that logs with similar dimensions float at varying depths, presumably because of differences in green density. After investigating further, however, he found that others had noted that floating logs in millponds may not accurately reflect their density. He assumed that this was caused by uneven taper, sweep, crook, or other dimensional features of the log. He hypothesized that if a uniform sample from a log could be obtained, this problem might be overcome. He then constructed a portable device to measure the displacement of water in a plastic container when an increment core was submerged.

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<sup>1/</sup> The xylodensimeter ("xylo" meaning wood) was designed by Gary Bergstrom, presently working as a logging specialist, USDA Forest Service, Rogue River National Forest, Medford, Oregon.

The Bergstrom xylo densimeter consists of a hydrometer and a plastic cylinder (flotation chamber) containing water. The hydrometer is calibrated to house an increment core of a specific diameter and length (fig. 1). The hydrometer is constructed of thin-walled aluminum and plastic. An increment core is inserted in the hydrometer and then floated in the plastic cylinder filled with distilled water. Green density (pounds per cubic foot) is read directly from the waterline on the graduated scale of the hydrometer. The instrument has been tested and successfully calibrated with homogeneous materials of known densities. The measurement of the green density of wood, essentially a heterogeneous material, and its application to estimating log weights is the next logical step in the evaluation process.

This study was designed to answer three questions about the performance of the Bergstrom xylo densimeter as a tool for estimating log and bole weights:

1. How accurately can it measure the green density of wood in recently cut logs compared with standard wood disk techniques?
2. Can this measurement of green density, combined with the volume of the log, estimate the weight of logs accurately?
3. How well do models developed from measurements on a small subsample of trees predict the weights of boles for trees in the same stands and from different stands?

We conducted two field studies with the Bergstrom xylo densimeter, one in the summer of 1981 and the other in the summer of 1982. After qualitative evaluations were conducted in the 1981 study, structural changes were made on the hydrometer element (fig. 1) to provide an easier means of inserting fragile increment cores.

## Objectives

Objectives were to estimate: (1) the accuracy and bias of the Bergstrom xylo densimeter in the measurement of green wood density, (2) the accuracy and bias of estimated log weights from calculated volumes and green densities measured with the Bergstrom xylo densimeter, and (3) the accuracy and bias of predicted tree bole weights from regression equations developed for one population of trees and applied to other populations.

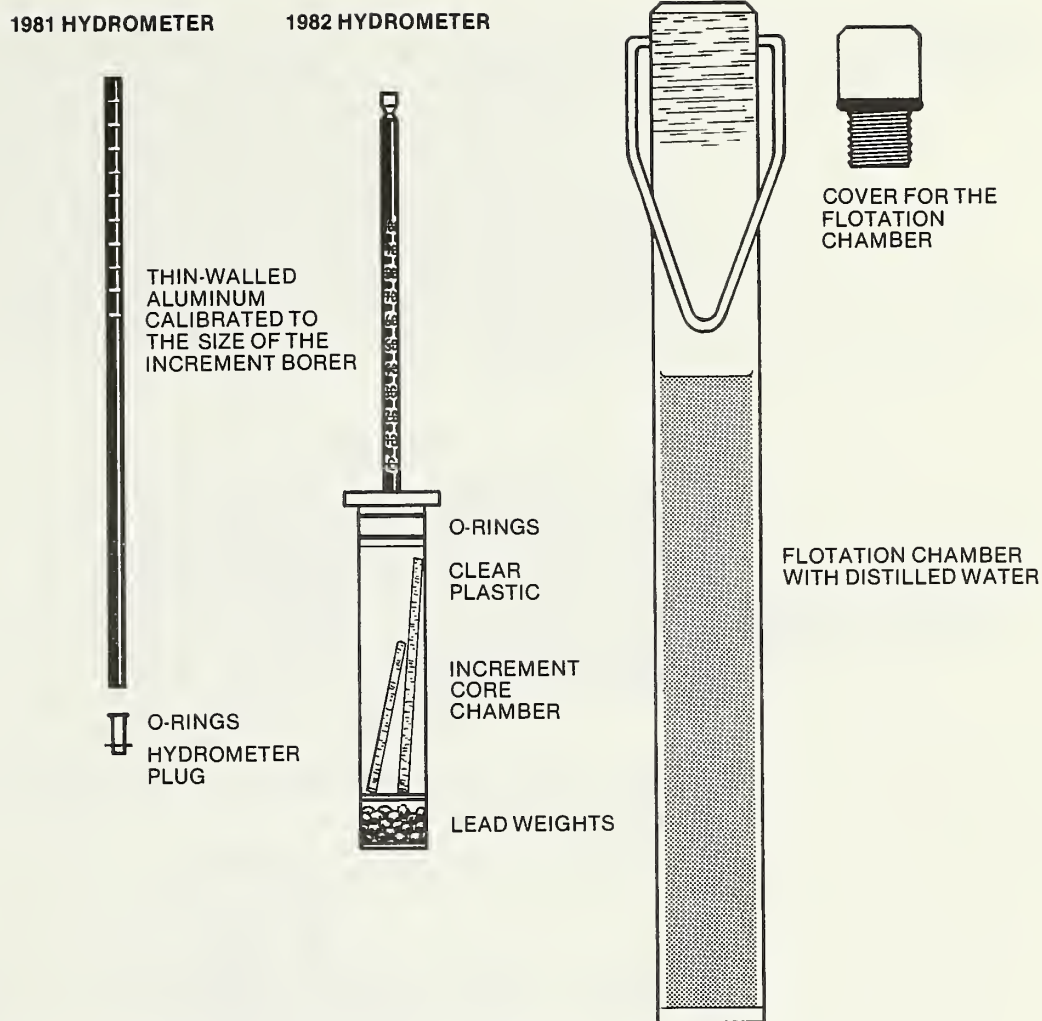


Figure 1.—A schematic of the Bergstrom xylodensimeter.

## Methods

### Study Area

Four study plots (three 5-acre plots and one 20-acre plot) were selected in the Wind River Experimental Forest (Trout Creek Hill Unit) on the Gifford Pinchot National Forest, southwest Washington. The principal species in the area are old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Secondary species are western red-cedar (*Thuja plicata* Donn ex D. Don) and true firs (*Abies* spp.).

## Selection of Sample Trees

Study trees from the four plots were selected from old-growth merchantable Douglas-fir and western hemlock, ranging in diameter at breast height (DBH)<sup>2/</sup> from 10 to 60 inches.<sup>3/</sup> The total number of western hemlock and Douglas-fir on the four plots was 1,876. This includes the combination of all trees for both the 1981 and 1982 studies. Each tree was assigned a sequential number. After stratification by species and diameters, 30 trees of each species were randomly selected from three 5-acre plots (1981 sample; plots 1 to 3) and 50 trees per species from one 20-acre plot (1982 sample; plot 4) (table 1). Because of problems in the load cell during weighing, one western hemlock and one Douglas-fir tree were deleted from the 1981 sample, leaving 79 trees per species for the entire study.

<sup>2/</sup> Diameter of tree bole at 4½ feet above ground level as measured on the uphill side of the tree.

<sup>3/</sup> Trees selected in the three 5-acre plots (1981 samples) were screened for major defects and external damage determined by a concurrent study of tree crowns. If defect or damage in a tree would jeopardize the safety of a tree climber, the tree was not selected.

**Table 1—Distribution of 79 sample trees by species and diameter class, southwestern Washington**

Diameter class <sup>1/</sup>	1981, plots 1-3		1982, plot 4	
	Western hemlock	Douglas-fir	Western hemlock	Douglas-fir
<u>Inches</u>				
10.0-15.5	2	0	6	0
15.6-20.5	4	0	5	2
20.6-25.5	7	2	6	4
25.6-30.5	3	3	9	8
30.6-35.5	7	4	7	6
35.6-40.5	4	4	4	8
40.6-45.5	2	2	8	8
45.6-50.5	0	5	4	8
50.6-55.5	0	2	1	6
55.6-60.5	0	7	0	0
Total	29	29	50	50

<sup>1/</sup> Diameter at breast height.

**Measuring Green Density  
by the Wood Disk  
Technique (1981 Sample)**

Trees were felled and bucked into segments with length restricted so that the weight of individual logs would not exceed the capacity of the front-end loader used to lift the logs for weighing. The bucking of logs began as a trial and error process until approximations of maximum log lengths could be established for a given diameter class. All logs were identified with coded tags after bucking.

Immediately after the felling operation, wood disks were cut from the large end of the butt log and at various intervals to the top of the bole (fig. 2). Four wedge-shaped pieces were cut radially along perpendicular diameters of each disk. Each wedge was divided into sapwood and heartwood zones. From each zone a sample, approximately 1.5 x 1.5 x 4 inches, was taken. These samples provided material for determining the radial profile of green density in the sapwood and heartwood

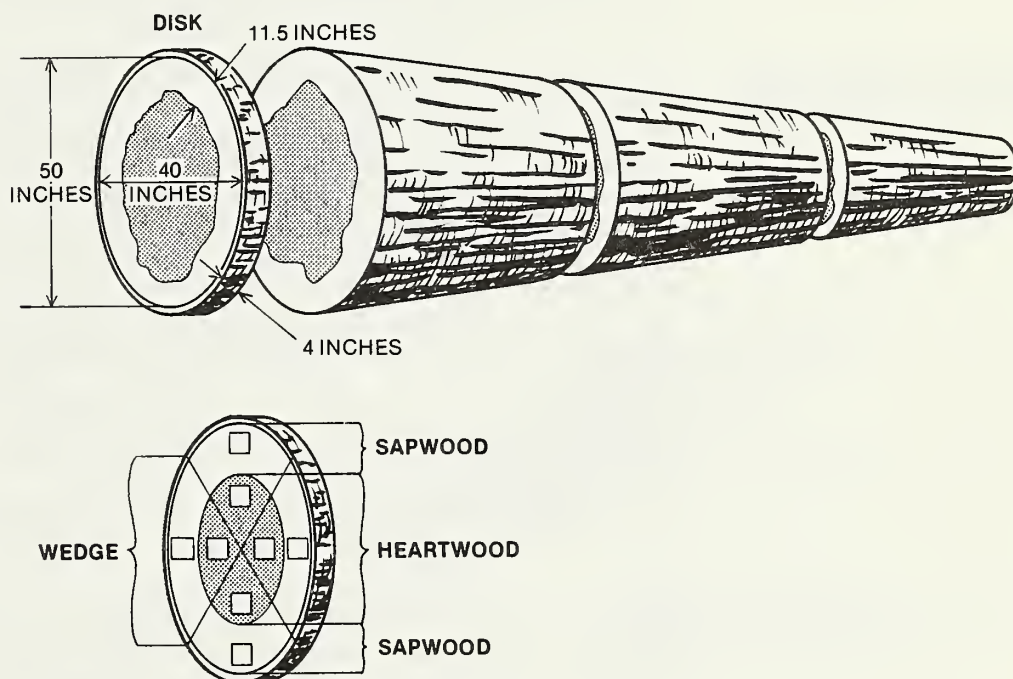


Figure 2.—The measurement of green density by the disk method.

An example of a "weighted average green density" computation for a single disk.

Green density averages (four samples per component):

Sapwood component = 52 lb/ft<sup>3</sup>.

Heartwood component = 48 lb/ft<sup>3</sup>.

Volume calculation:

Volume (ft<sup>3</sup>) =  $(\pi)(\text{radius})^2(\text{disk thickness})/1728$ .

Total wood volume in the disk =  $(\pi)(45 \text{ inches}/2)^2(4 \text{ inches})/1728$   
= 3.68 ft<sup>3</sup>.

Heartwood volume in the disk =  $(\pi)(22 \text{ inches}/2)^2(4 \text{ inches})/1728$   
= 0.88 ft<sup>3</sup>.

Sapwood volume in the disk = 3.68 ft<sup>3</sup> - 0.88 ft<sup>3</sup>  
= 2.80 ft<sup>3</sup>.

Sapwood weight =  $(52 \text{ lb/ft}^3)(2.80 \text{ ft}^3)$   
= 145.60 lb.

Heartwood weight =  $(48 \text{ lb/ft}^3)(0.88 \text{ ft}^3)$   
= 42.24 lb.

Total weight = 187.84 lb.

Weighted average green density =  $187.84 \text{ lb}/3.68 \text{ ft}^3$   
= 51.04 lb/ft<sup>3</sup>.

regions of the disk. Each density sample was labeled so that its location in the tree could be traced radially and longitudinally. The number of disks cut per tree depended on tree size and log length. Logs with small diameters had only one radial sample taken for each wedge-shaped section because of the lack of heartwood in logs of the upper crown. Samples were taken to the laboratory in sealed, tared containers for further analysis.

In the laboratory, the green weight of each sample was measured and the volume was determined by immersing the sample in water (Brown and others 1952). The green density of the sample was calculated by dividing the weight of the sample by its green volume. An average green density was computed for the four radial samples extracted from the sapwood and heartwood zones of the disk. A single weighted green density was then determined from volumetric proportions of sapwood to heartwood. An example is presented in figure 2.

#### **Measuring Green Density With the Xylodensimeter (1981 and 1982 Samples)**

After disk sampling (1981 samples), two increment cores were taken at each sample point (one core from above and one from below the disk sample). Volumetric proportions of sapwood to heartwood in the logs were duplicated in the cores by cutting them to a 6-inch length in approximately the same percentage, by volume, of the sapwood and heartwood components in the log. Two radial measurements were needed so that appropriate proportions of sapwood to heartwood could be applied to the core for each sample point; these were the diameter inside bark (DIB) and inches of sapwood (IOS). The DIB was measured from the cross section of the log at the sampling point (average of the long and short diameters). The IOS was measured directly from the extracted core.

The following equation provides the percentage of sapwood (%S) needed in the core to duplicate the proportion of sapwood in the log:

$$\%S = \frac{(DIB)^2 - ((DIB) - 2(IOS))^2}{(DIB)^2} (100) = \frac{4(IOS)(DIB - IOS)}{(DIB)^2} (100). \quad (1)$$

Equation 1 was programed into a calculator and was also presented as a series of curves for various combinations of DIB and IOS (fig. 3); for example, from either equation 1 or figure 3, a log with a 30-inch DIB and 3.3 inches of sapwood would have 39 percent sapwood.

The increment core was placed in a "core length cutter guide" and cut with a sharp knife to the correct length (fig. 4). The metal L-shaped device has a scale for percentage of sapwood inscribed on the surface. The heartwood to sapwood transition of the core was placed adjacent to the inscribed %S, as calculated from equation 1 or read from the curves, (fig. 3), and the core was cut flush at both ends of the guide. The process results in a 6-inch increment core with the same estimated ratio of heartwood to sapwood volume as that of the log.

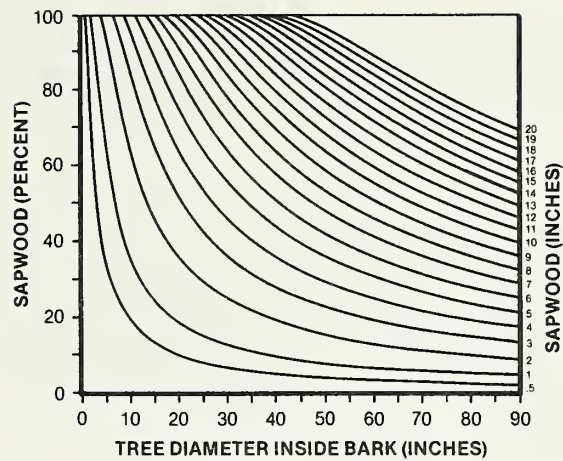


Figure 3.—Curves showing percentage of sapwood.

$$\text{Sapwood (percent)} = \frac{4(\text{IOS})(\text{DIB}-\text{IOS})}{(\text{DIB})^2} (100).$$

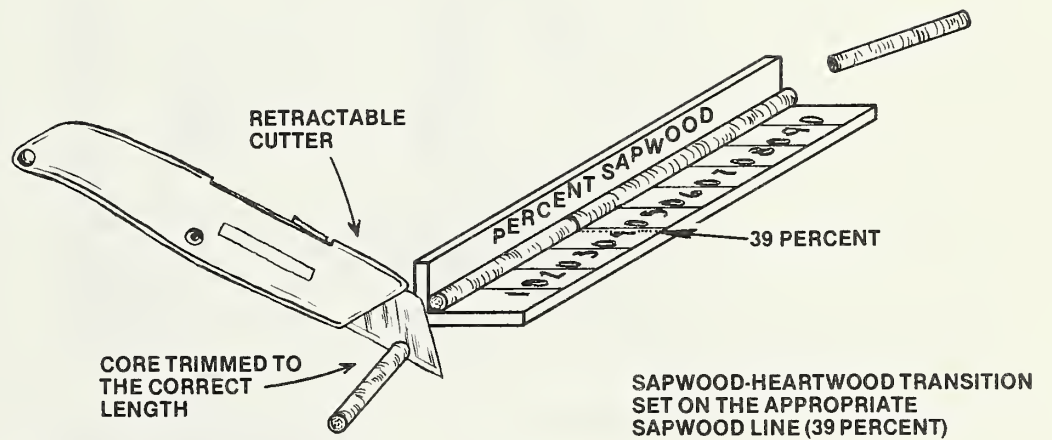


Figure 4.—Core length cutter guide.

The core was then placed in the hydrometer and lowered into the water-filled flotation chamber (fig. 1). A reading taken at the intersection of the waterline with the graduated scale of the hydrometer gave the green density of the core. Figure 5 illustrates the procedure.

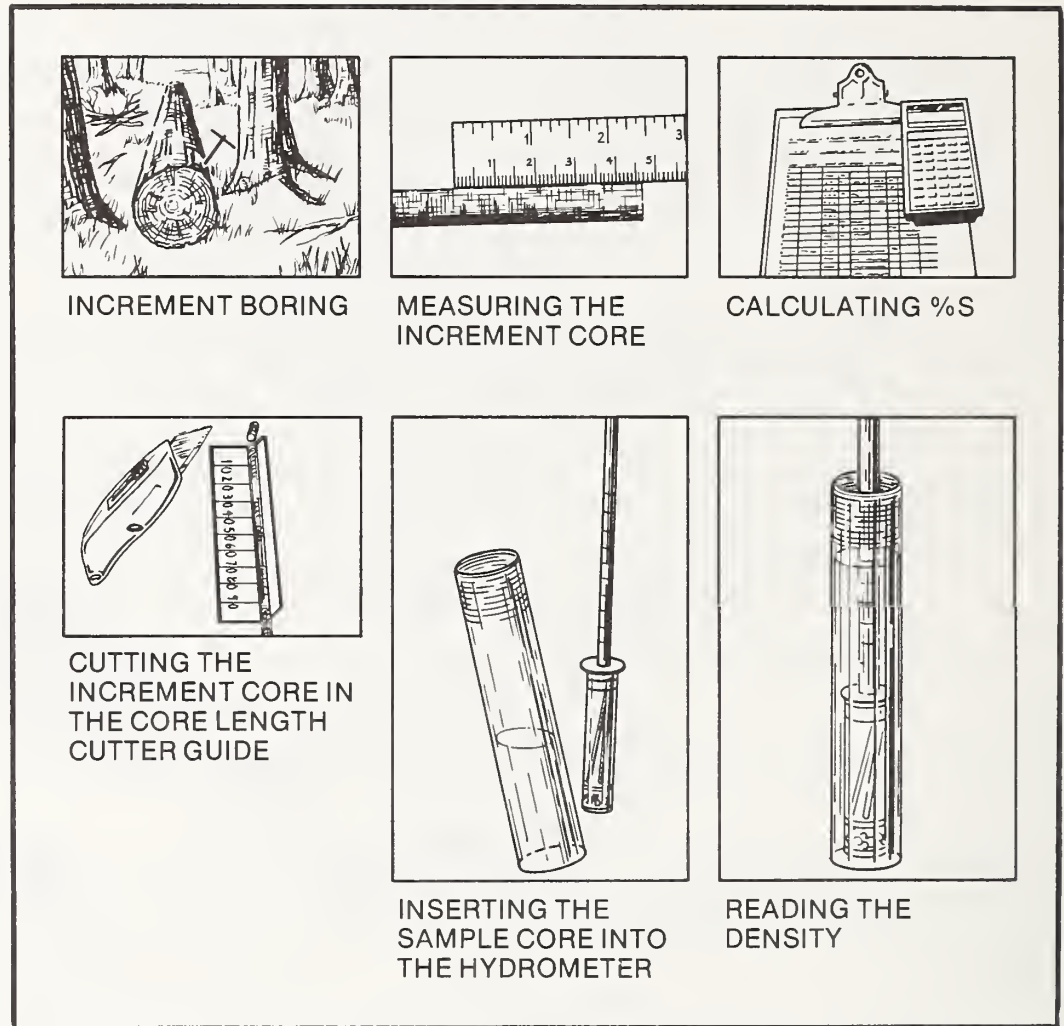


Figure 5.—The process of measuring green density with the Bergstrom xylo densimeter.

#### Comparison of the Wood Disk Technique With the Xylo densimeter Technique (1981 Sample)

Estimates of green density by the wood disk technique were compared with estimates by the xylo densimeter in terms of the mean of the differences and the mean of the absolute differences for paired observations in both western hemlock and Douglas-fir. The comparison provided an estimate of bias (mean of the differences) and absolute error (mean of the absolute differences) for the xylo densimeter in terms of the values obtained from the wood disk measurement.

**Calculating Log Weights  
From Densities Obtained  
With the Xylodensimeter  
(1982 Sample)**

Each log was scaled for gross cubic volume after it was sampled for density. Log-end diameters (outside bark) were measured on the cross section of the log to the nearest (0.1) inch and the lengths to the nearest (0.1) foot. Volumes for Douglas-fir butt segments were calculated by Bruce's (1982) butt log equation:

$$V = CL(0.25D^2 + 0.75d^2); \quad (2)$$

for western hemlock butt segments by the sub-neiloid rule, for midsegments of both species by the Smalian rule, for top segments of both species by the two-end conic rule (Dilworth 1981):

sub-neiloid rule:

$$V = CL \frac{(D + d)^2}{2}; \quad (3)$$

Smalian rule:

$$V = CL \frac{(D^2 + d^2)}{2}; \quad (4)$$

two-end conic rule:

$$V = CL \frac{(d^2 + D^2 + Dd)}{3}; \quad (5)$$

where:

V = volume of the log in cubic feet;

C = 0.005454 (unit conversion factor);

L = length of the log in feet;

D = average diameter outside bark for the large end of the log in inches; and

d = average diameter outside bark for the small end of the log in inches.

The end area of the log was used as the weighting factor to calculate a green density value for each log:

$$\text{Average green density} = \frac{(D)^2 (K) + (d)^2 (k)}{2 \left[ \frac{(D + d)}{2} \right]^2}; \quad (6)$$

where:

K = green density of the core measured at the large end of the log in pounds per cubic foot (lb/ft<sup>3</sup>); and

k = green density of the core measured at the small end of the log in lb/ft<sup>3</sup>.

Figure 6 illustrates a typical Douglas-fir butt log with various dimensions and densities. The calculated average green density for this particular log equals 38.0 lb/ft<sup>3</sup>. The volume multiplied by the weighted green density equals the calculated weight (6,881 lb). Note that the bark is considered part of the gross wood volume and receives an average density value equal to that calculated for the wood. Log weights were not calculated from densities by the wood disk technique because of insufficient sampling points along the bole of each tree.

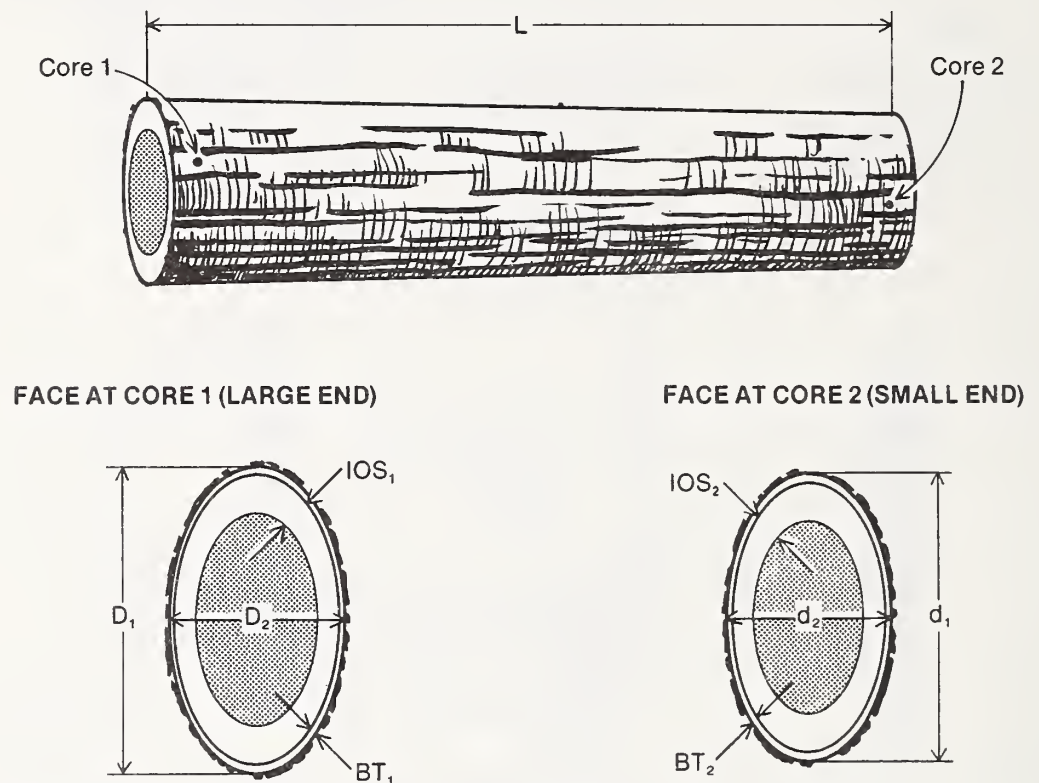


Figure 6.—A technique for calculating log weights with the Bergstrom xylodensimeter.

**Measurements:**

- $D_1$  = longest diameter (DOB) = 50 inches.
- $D_2$  = shortest diameter (DOB) = 40 inches.
- Average diameter ( $D$ ) = 45 inches.
- $BT_1$  = single bark thickness = 2.5 inches.
- $BT_2$  = single bark thickness = 2.25 inches.
- $d_1$  = longest diameter (DOB) = 45 inches.
- $d_2$  = shortest diameter (DOB) = 40 inches.
- Average diameter ( $d$ ) = 42.5 inches.
- $IOS_1$  = inches of sapwood (large end of the log) = 2.25 inches.
- Percentage of sapwood (see eq. 1) = 21.
- Density reading of the large end = 39 lb/ft<sup>3</sup>.
- $IOS_s$  = inches of sapwood (small end of the log) = 2 inches.
- Percentage of sapwood = 20.
- Density reading of the small end = 37 lb/ft<sup>3</sup>.

**Calculations:**

$$\text{Average density of the log} = \frac{(45)^2(39) + (42.5)^2(37)}{2[(45 + 42.5)/2]^2} = 38.09 \text{ lb/ft}^3.$$

$$L = \text{log length} = 17.8 \text{ feet.}$$

$$\begin{aligned} \text{Volume (eq. 2)} &= (0.005454)(17.8)[(0.25)(45)^2 + (0.75)(42.5)^2] \\ &= 180.66 \text{ ft}^3. \end{aligned}$$

$$\begin{aligned} \text{Calculated weight} \\ \text{of the log} &= (180.66 \text{ ft}^3)(38.09 \text{ lb/ft}^3) \\ &= 6,881 \text{ lb.} \end{aligned}$$

**Measuring Log Weights  
(Lifted Weights) and  
Comparing Them With  
Calculated Weights  
(1981 Sample)**

Each log was weighed by use of a load cell attached to a front-end loader. Weights of logs lifted by the load cell were compared with calculated weights in terms of bias and absolute error.

**Calculating Bole Weights  
From Densities Measured  
With the Xylodensimeter  
(1982 Sample)**

Sample trees of both species were divided into two random subsamples of 25 trees for model construction measurements and for model validation purposes (20-acre plot only). After felling, each tree was partitioned into a lower section (approximately one-third of the merchantable height) and an upper section (the remaining bole). The merchantable height was to a 6-inch top (DIB). Diameter outside bark (DOB) and bark thickness were measured in the lower section every 3 feet from the stump; DOB was measured with a diameter tape or steel calipers, and bark was measured with a steel ruler after it was chopped. An increment core was extracted every 6 feet and a modified Bergstrom xylodensimeter (fig. 1) was used to determine density of the extracted cores. This procedure produced a succession of diameter and density readings for the bole.

Volumes were calculated by the Smalian rule (eq. 4) for each 3-foot subsection and were converted to green weight by multiplying the values by an appropriate green density. The weights of all the 6-foot subsections were totaled for the weight of the lower bole.

The upper section of the merchantable bole was divided into eight equal subsections. Diameters outside bark and bark thickness were measured at each division. Increment cores were extracted for measurement of density at the fourth and sixth diameter locations (fig. 7).

The volumes of the upper subsections were calculated by Newton's formula (Dilworth 1981):

$$V = CL \frac{(d^2 + 4M^2 + D^2)}{6}; \quad (7)$$

where:

$M$  = diameter outside bark for the middle of the log in inches.

Because green density was not measured for each corresponding volume calculation (subsection), green density values were interpolated by calculating the change in green density as a function of length between actual density measurements (fig. 7). In the extreme upper bole, the green density at the sixth diameter location was used for the remaining subsection(s). The weights for each subsection were added to produce the weight for the upper bole. The lower and upper sections were then added together to determine the calculated bole weight.

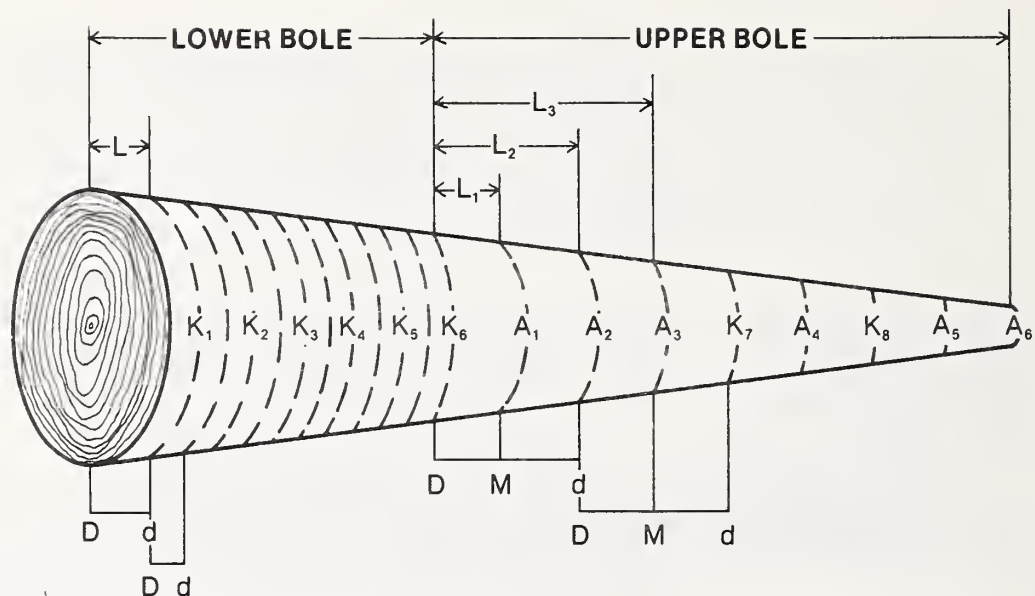


Figure 7.—Calculation of bole weights.

**Lower bole:**

$$\text{Volume, Smalian } (V_1) = CL \frac{(D^2 + d^2)}{2}.$$

$$\text{Weight of a subsection } (W_i) = (V_i)(k_i).$$

$$\text{Weight of the lower bole} = \sum_{i=1}^n (W_i).$$

**Upper bole:**

$$\text{Interpolated green density } (A_1) = k_6 + \frac{(k_7 - k_6)}{L_3} (L_1).$$

$$\text{Volume, Newton } (V_1) = \frac{(D^2 + 4M^2 + d^2)}{6} (C) (L_2).$$

$$\text{Weight of a subsection } (W_1) = (V_1)(A_1).$$

$$\text{Weight of the upper bole} = \sum_{i=1}^n (W_i).$$

Where:

D = diameter outside bark, large end.

M = diameter outside bark, middle.

d = diameter outside bark, small end.

C = 0.005454.

L = length of segment.

$L_i$  = length in feet,  $i = 1, 2, \dots, n$ .

$k_i$  = measured green density;  $i = 1, 2, \dots, n$ .

$A_i$  = interpolated green density;  $i = 1, 2, \dots, n$ .

$A_e$  = extrapolated green density;  $e = 5, 6$ .

## Measuring Lifted Weights and Comparing Them With Calculated Bole Weights (1982 Sample)

Logs from the lower and upper sections were weighed by use of a load cell attached to a front-end loader. The bias and absolute error were computed to compare the calculated weight of the entire bole with the lifted weight. The procedure provides the means to investigate weight relationships for single logs, groups of logs, and entire boles.

## The Development and Validation of Bole Prediction Equations (1982 Sample)

For both Douglas-fir and western hemlock, calculated bole weight (calculated volume multiplied by the measured green density is the dependent variable) was regressed against DBH and total tree height (the independent variables) to produce weight prediction models. The validation subsamples and additional offsite samples provided an indication of bias and absolute error for the calculated bole weight equations.

## Results

### Comparison of the Wood Disk Technique With the Xylodensimeter Technique

Table 2 shows the comparison of green densities derived from the wood disk techniques with green densities from the xylodensimeter. The estimates of green density were similar to those of the wood disk technique. The bias was negligible, and the absolute error was within 8 percent for all positions along the bole.

**Table 2—Comparison of the wood disk technique with the xylodensimeter technique, 1981 sample logs**

Position in tree and species	n 1/	Wood disk mean 2/	Bergstrom xylodensimeter mean	Bias 3/	Relative bias 4/	Mean absolute difference 5/	Mean relative absolute difference 6/
		Pounds per cubic foot			Percent	Pounds per cubic foot	Percent
Butt log:							
Western hemlock	28	48.9	49.2	0.30	0.6	3.80	7.8
Douglas-fir	28	41.0	40.5	-.50	-1.2	3.06	7.5
Middle log:							
Western hemlock	28	49.5	48.9	-.60	-1.2	3.40	6.9
Douglas-fir	28	38.3	37.8	-.50	-1.3	2.51	6.6
Top log:							
Western hemlock	26	54.4	52.2	-2.20	-4.0	4.10	7.5
Douglas-fir	26	37.7	36.8	-.88	-2.3	2.35	6.2

1/ Number of paired samples.

2/ Volumetrically weighted green wood (sapwood + heartwood) densities.

3/ Bias is the mean of the differences between the disk and the xylodensimeter densities.

4/ Bias divided by wood disk mean multiplied by 100.

5/ Accuracy measure; the mean of the absolute differences between the disk and the xylodensimeter densities.

6/ Mean absolute difference divided by wood disk mean multiplied by 100.

## Comparison of Lifted and Calculated Log Weights

Table 3 shows the comparison of calculated weights derived from an average density applied to an appropriate volume formula with lifted weights measured by a load cell. The bias was slightly negative for both species and all log positions. The absolute error was under 9 percent.

**Table 3—Lifted weights and calculated weights, 1981 sample logs**

Position in tree and species	n <u>1/</u>	Mean lifted weight <u>2/</u>	Mean calculated weight <u>3/</u>	Bias <u>4/</u>	Relative bias <u>5/</u>	Mean absolute difference <u>6/</u>	Mean relative absolute difference <u>7/</u>
		-----Pounds-----			Percent	Pounds	Percent
Butt log:							
Western hemlock	28	4,020	3,986	-34	-0.8	343	8.5
Douglas-fir	28	6,292	6,095	-197	-3.1	489	7.8
2d log:							
Western hemlock	26	3,176	3,152	-24	-.8	267	8.4
Douglas-fir	27	4,501	4,446	-55	-1.2	255	5.7
3d log:							
Western hemlock	27	2,760	2,671	-89	-3.2	203	7.4
Douglas-fir	29	3,989	3,896	-93	-2.3	258	6.5
4th log:							
Western hemlock	20	2,637	2,573	-64	-2.4	210	8.0
Douglas-fir	25	3,835	3,743	-92	-2.4	282	7.4
Crown log:							
Western hemlock	11	1,881	1,849	-32	-1.7	118	6.3
Douglas-fir	23	3,339	3,223	-116	-3.5	219	6.8

1/ Number of paired samples.

2/ Measured with a load cell.

3/ Calculated with a xylodensimeter density and cubic volume formula.

4/ Bias is the mean of the differences between the lifted and the calculated weights.

5/ Bias divided by mean lifted weight multiplied by 100.

6/ Accuracy measure; the mean of the absolute differences between the lifted and the calculated weights.

7/ Mean absolute difference divided by mean lifted weight multiplied by 100.

## Evaluation of Weight Prediction Equations

Table 4 summarizes the regression equations developed from the calculated weights. Total tree height was not a significant variable (F-test) for Douglas-fir. Equations for the calculated weights were used in predicting weights for whole boles of the 25 validation trees (table 5). By use of the same equations, bole weights for trees felled and bucked in 1981 from the three 5-acre plots were also predicted. With the exception of plot 3, the bias and absolute error of the prediction models remained within 20 percent. The large error in plot 3 was presumably due to the small size of the trees. Note the lower mean lifted weights for plot 3 compared with the other plots in table 5. This difference may be indirectly the result of the biological and physical factors of the site or a change in green density with time from 1981 to 1982 or both. Because of the lack of specific site information (for example, soil type, water-holding capacity), conclusions regarding influence of the site require further research.

**Table 4—Calculated weight prediction equations, 1982 sample**

Species	Prediction equations 1/	Sample size	R <sup>2</sup> 2/	Mean square error 3/
Douglas-fir	$W = \exp(1.594 + 2.292(\ln(\text{DBH})))$ 4/	25	0.98	2442.2
Western hemlock	$W = \exp(1.794 + 2.315(\ln(\text{DBH})))$	25	.97	2415.7
Western hemlock	$W = \exp(-1.202 + 1.961(\ln(\text{DBH})) + 0.8374(\ln(\text{HT})))$	25	.97	2511.6

1/ W = green weight of the bole in pounds; exp = 2.7183 to the power enclosed in parentheses; ln = natural logarithm; DBH = diameter at breast height in inches; HT = total height of the tree in feet.

2/ Coefficient of determination.

3/ For logarithmic functions, the mean square error of the residuals was calculated as the sum of the predicted minus the sum of the observed divided by the degrees of freedom, transformed to arithmetic units.

4/ The mean square error of residuals from transformed data divided by 2 was added to the intercept regression coefficient to correct for transformation bias (Baskerville 1972).

**Table 5—Bias and accuracy evaluation of bole weight, 1982 samples**

Population sample 1/ and species	n 2/	Lifted mean 3/	Calculated mean 4/	Bias 5/	Relative bias 6/	Mean absolute difference 7/	Mean relative absolute difference 8/
		-----Pounds-----			Percent	Pounds	Percent
Model trees, plot 4:							
Western hemlock	25	20,409	20,144	-265	-1.3	999	4.9
Douglas-fir	25	20,613	21,768	1,155	5.6	1,205	5.8
WITHIN POPULATION COMPARISON (TREES FROM THE SAME AREA)							
Validation trees, plot 4:							
Western hemlock	25	12,460	12,282	-178	-1.4	735	5.9
Douglas-fir	25	22,122	22,987	866	3.9	2,213	10.0
BETWEEN POPULATION COMPARISON (TREES FROM DIFFERENT AREAS)							
Plot 1:							
Western hemlock	14	14,974	14,548	-426	-2.8	1,729	11.5
Douglas-fir	13	26,818	30,251	3,433	12.8	5,379	20.1
Plot 2:							
Western hemlock	13	18,047	18,257	210	1.2	2,257	12.5
Douglas-fir	11	34,032	35,152	1,120	3.3	4,541	13.3
Plot 3:							
Western hemlock	3	2,340	2,817	477	20.4	495	21.1
Douglas-fir	5	7,123	8,554	1,431	20.1	1,617	22.7

1/ Observations used to build the regression equations. The equations were single predictor models (DBH) developed from the calculated weights. The western hemlock equation is  $\text{weight (lb)} = \exp(1.794 + 2.315(\ln(\text{DBH})))$  and the Douglas-fir equation is  $\text{weight (lb)} = \exp(1.594 + 2.292(\ln(\text{DBH})))$ . Validation trees were used to test the accuracy and bias of the equations. Model trees and validation trees are from plot 4 and were sampled in the summer of 1982. Trees in plots 1 to 3 are from 3 different areas measured in the summer of 1981.

2/ Number of paired samples.

3/ Measured with a load cell.

4/ Calculated with a xylodensimeter.

5/ Bias is the mean of the differences between the lifted and the calculated weights.

6/ Bias divided by mean lifted weight multiplied by 100.

7/ Accuracy measure; the mean of the absolute differences between the lifted and the calculated weights.

8/ Mean absolute difference divided by mean lifted weight multiplied by 100.

## Discussion

This study examines two phases of weight estimation for heavy-lift logging: green density measurement and model development. The first phase (1981) compares two techniques for measuring green density of wood, the Bergstrom xylodensimeter and the standard wood disk technique (table 2). The absolute error between the two techniques ranged from about 3 pounds per cubic foot in the butt logs to just over 2 pounds per cubic foot in the crown logs for old-growth Douglas-fir. The absolute error was higher for western hemlock; the butt logs were slightly under 4 pounds per cubic foot, the crown logs just over 4 pounds. The bias was negligible for both species and all bole positions.

Qualitative differences also exist between the two techniques. The primary advantage of the disk method is the ability to measure green density for individual structural components such as sapwood, heartwood, and bark. Dry density, green density, and moisture content may be considered separately for each sample disk. In addition, variation around the circumference of the bole is taken into account when the samples within a single disk are averaged. This may explain, in part, the observed absolute error between the two techniques. The disadvantages of the wood disk method include the high costs of sampling because of the time and labor needed for each measurement, the requirement of a laboratory with expensive scales and ovens, the destruction of the bole for each sample tree, and the inability to record density measurements directly in the field.

The attractive qualitative feature of the xylodensimeter technique is the ability to measure the green density of a log with the appropriate ratios of sapwood and heartwood contained in the sample. The method is not labor intensive and materials are inexpensive. Furthermore, numerous measurements can be taken relatively fast along the length of the bole. The readings are recorded directly in the field, and the technique is not as destructive to the bole as is the disk method. The principal disadvantage of this technique is the limited amount of information obtained per observation. The increment core is quite small in proportion to the size of the log; for example, an increment core with a diameter of 0.169 inch and a length of 6 inches has a volume equal to 0.000078 cubic foot. The sample core volume from the butt log in figure 6 is only equal to 0.00004 percent of the log volume. In addition, unless increment cores are taken around the bole at each height, the circumferential variation in density is not considered.

Estimates of log weights were determined from densities measured with the xylodensimeter (table 2). The results were better than expected when the sizes of the sample cores compared with those from the larger logs are considered. The bias indicators were low in all bole positions for both Douglas-fir and western hemlock (table 3).

In the second phase (1982) of the study, fewer trees (25) were selected but more measurements were taken. Equations were developed (table 4) from data from a small subsample and applied to other trees within the same population and from other populations. The results were good in view of the potential variation in density and volume of old-growth trees. Although the application of an equation developed in one area and applied to other areas may have caused an increase in absolute error for both species, the error in Douglas-fir was consistently higher than in western hemlock (table 5). The higher absolute error in Douglas-fir was believed to be caused by extensive heart rot in the butt section of the boles. Decay made it difficult to obtain a complete increment core.

## How To Use the Xylodensimeter for Measuring Log and Bole Weights

The empirical bole model developed with calculated weights (1982) was evaluated to determine if weight prediction equations could be developed for a harvesting unit without lifting and weighing the boles. The results suggest that weights calculated with densities from the xylodensimeter may offer an alternative to lifting and weighing the boles. In areas of isolated or rugged terrain, where a preharvesting estimate of bole weight is needed, a forester could develop weight prediction equations from measurements of volume and green density.

**Estimating log weight.**—Figure 6 illustrates a method of determining individual log weights. The user must be able to identify the log's original position in the bole after bucking so that the appropriate volume equation can be applied. For example, a two-end conic rule is not an appropriate equation for the butt log. Logs in the field must also be physically separated so that diameters of log ends can be measured. A power-assisted increment boring tool that will increase the efficiency of the green density measurement is being investigated.

**Predicting bole weight.**—Figure 7 illustrates a method of measuring and developing prediction equations for total bole weight. We assumed that the variation in green density and the error associated with the calculation of volume in the lower portion of the bole would be higher than in the upper sections. This assumption was based on the fact that these logs can have atypical moisture conditions in the heartwood region because of pathological influence. Furthermore, in many aerial logging operations, the most critical estimate of weight is for the lower segment (butt log) because of the high value of the log. The data suggest that this assumption of high variation in the lower portion of the bole was indeed true; however, the upper section also demonstrated a high degree of variation in green density with height. There appears to be a change in green density in the upper bole of about 2 pounds per cubic foot with every 10 feet of height. This change was not necessarily in one direction. Green density actually decreased with height in two western hemlock trees, whereas it increased in the rest of the trees. In most applications, this variation may have little consequence because the bucked logs from the upper region of the bole are smaller and weigh considerably less than the lower logs. The concerned user may desire to take green density measurements at every diameter location in the upper section and avoid the interpolation of green density values.

In addition, the results suggested that the variation in green density within trees is equal to, or greater than, the variation between trees for specific locations. The user may wish to select fewer sample trees and to measure them more intensively. Bole weight prediction equations should be used with caution outside the specific area of development; for example, from a north aspect to a south aspect or from a ridgeline to a lower slope. Generally, we found that the absolute error increased for validation trees from different areas (table 5). Further research is needed on the effects of site on weight prediction equations.

## Problems and Further Applications

Considerable variation in green density with height in old-growth Douglas-fir and western hemlock was discovered during the research on and development of the Bergstrom xylodensimeter. Therefore, measurements of green density taken at a specific location along the bole may or may not represent density at other locations. In addition, a technique to merge an iterative volume calculation with height is needed so that a user can compute the volume and weight of bole segments before logs are bucked. Research is being done to solve these problems.

The development and refinement of the weight prediction model currently underway will provide the user with a method of data collection and computation of prediction equations that is site-specific. The model will consider the weight of any bole segment, the total bole weight, and the bucking length options to achieve specific weight objectives for various size trees and lift capacities.

## Conclusions

The Bergstrom xylodensimeter is useful for measuring wood densities, which can be applied to the estimation of log and bole weights. This new approach to estimating log weights promises to be useful for planning and conducting logging operations, especially with logging systems that have weight limits. The instrument is faster, more economical, and less destructive than the disk sampling technique.

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## Metric Conversions

English units	Multiplication factor	Metric units
inches	2.540	centimeters
feet	0.305	meters
cubic feet	0.028	cubic meters
pounds	0.454	kilograms
acres	0.405	hectares
pounds per cubic foot	16.019	kilograms per cubic meter
cubic feet per acre	0.070	cubic meters per hectare

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**Waddell, Dale R.; Lambert, Michael B; Pong, W. Y.** Estimating tree bole and log weights from green densities measured with the Bergstrom xylo densimeter. Res. Pap. PNW-322. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 18 p.

The performance of the Bergstrom xylo densimeter, designed to measure the green density of wood, was investigated and compared with a technique that derived green densities from wood disk samples. In addition, log and bole weights of old-growth Douglas-fir and western hemlock were calculated by various formulas and compared with lifted weights measured with a load cell attached to a front-end loader. The Bergstrom xylo densimeter accurately measured green wood density and is useful for estimating log weights.

**Keywords:** Log measurements, boles, wood density, cubic volume measure, measuring equipment, old-growth stands.

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